

Comparison of Two Detection Combination Algorithms for Phased Array Radars

Zhen Ding and Peter Moo
Wide Area Surveillance Radar Group
Radar Sensing and Exploitation Section
Defence R&D Canada
Ottawa, Canada

Zhen.ding@drdc-rddc.gc.ca, Peter.Moo@drdc-rddc.gc.ca

Abstract — Phased array radars have been widely studied. One issue observed is that adjacent radar beams detect the same target. This multiplicity is resulted from a few factors such as the radar beam spacing, radar power, target size and trajectory etc. It degrades the radar performance greatly by asking for redundant confirmation beams and therefore increasing the false track rate. No public solutions to detection combination have been reported. This paper provides a comparison of two straight forward detection combination algorithms: cross-line combination and in-line combination. The raw multiple detection data were generated by a simulator of multi-function radar (MFR) and the combination algorithms are evaluated with the recorded simulation data. With the given radar setup, the cross-line combination algorithm needs to buffer 2-3 scanned lines of data and the delay is about 2-3 seconds. The in-line combination algorithm reduces the buffer to one scanned line of data and its delay is about 1 second. However, the first algorithm is able to remove about 2/3 of raw detections and achieve a better performance of noise suppression. The later can reduce about 1/3 of the raw detection, with less noise suppression.

Keywords — Multi-function phased array radar, beam-space, detection combination, performance evaluation

I. INTRODUCTION

An electronically scanned phased array Multi-Function Radar (MFR), is a type of radar whose transmitter and receiver functions are composed of numerous small transmit/receive modules. An MFR can perform many functions previously performed by individual, dedicated radars for search, tracking and weapon guidance. It can also be used effectively for secure communications [1]. In an MFR, the radar surveillance plays a critical role to optimize the radar performance. The surveillance usually takes more time than other functions. Any redundant detections from the surveillance beams needs radar time for processing and this leaves less time for other radar functions. In this paper, we use the Adapt_MFR, an MFR simulator, to investigate the detection combination algorithms.

The Adapt_MFR simulator was developed by DRDC Ottawa has through several contracts with Atlantis Scientific Inc., Sicom System Ltd. and C-Core [2, 3]. The MFR simulator had different names over the years such as MFARSIM,

RMFARSIM, and ADAPT_MFR. The latest version ADAPT_MFR was used in this study. Adapt_MFR is coded in MATLAB and runs on a Windows platform. The Adapt_MFR has been developed specifically to evaluate the detection capability of an MFR against anti-ship missiles (ASM) operating in littoral environments. Both rotating and non-rotating phased array MFR can be simulated, as well as, conventional rotating antennas such as volume search radars.

The Adapt_MFR performs four main functions: search, confirmation, tracking and cued search. Each of them occupies amount of time, energy and computation resources. The search function is fundamental to a phased array MFR since other functions (such as tracking) depend on its performance. A search waveform is specially designed to optimize the performance of an electronically steering beam. Different waveforms are useful for different regions or searching sectors. Once the waveforms are chosen for the search beams, one must consider the following two issues:

- Firstly, how to arrange the beam positions?
- Secondly, how to consolidate detections coming from the same target?

This study focuses on the second problem. A simulation study of two detection combination algorithms is done. Note that the two issues are closely related with each other. Wide beam space means that less beam positions are needed to cover the surveillance region and the total number of redundant detections turns to be less. However, the radar could miss some targets. On the other hand, small beam space means that a lot more beams are needed to cover the same search region. The high density of beams results in more duplicate detections. An advantage of using a narrower beam space is that the radar is more likely to detect the target with better accuracy.

The reminder of the paper is arranged as follows. A high level description of the Adapt_MFR is given in Section 2. Section 3 describes the detection procedure of a search beam. Radar setup and evaluation of detection combination algorithms are presented in Section 4. Section 5 concludes the paper.

II. ADAPT_MFR SIMULATOR

ADAPT_MFR is a full radar simulation package, and it has been designed to evaluate the detection capability of naval multifunction radar(s) (MFRs) and conventional radars against anti-ship missiles (ASM) operating in a littoral environment. The package has evolved from a basic, non-causal simulation that was exclusively designed to examine maritime-based operation of a single phased-array radar. Support for both rotating and non-rotating phased array MFRs, as well as conventional rotating dishes such as volume search radars, is included. It incorporates models for land, sea, chaff, rain and angel clutter (flocks of birds or insects), as well as jammers. ADAPT_MFR runs causally (as of course a real radar system would), producing detection output results for one beam (dwell) at a time. Multiple waveforms and radar operational modes are available, including the dynamic and adaptive switching of waveforms. Multiple radars may communicate and interact, with two-way feedback also provided for an external tracking system. ADAPT_MFR also includes the ability to model waveform propagation with TERPEM software, and incorporate real terrain features through the importation of DTED (Digital Terrain Elevation Data) files.

An illustration of the high-level simulation architecture is presented in Figure 1. The framework consists of a series of modules that are used to prepare, process or interpret any significant system element or generated simulation data. In practice, they are defined through the user interface and stored in associated data structures. The simulator is also equipped with an Interacting Multiple Model (IMM) tracker [3].

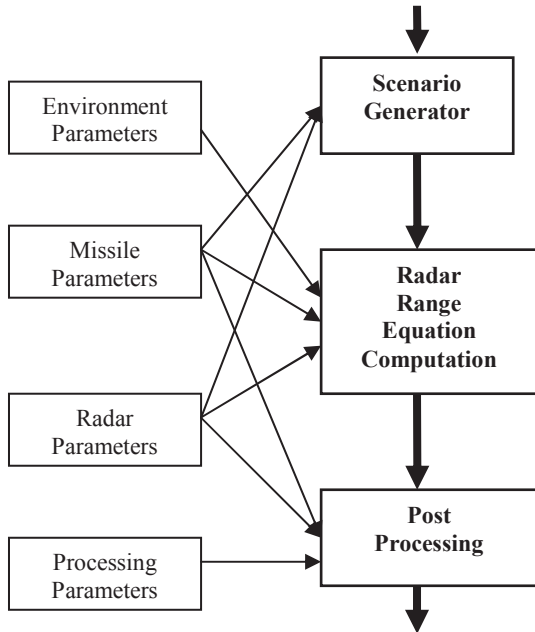


Figure 1 High-level architecture of ADAPT_MFR.

The simulation modules provide all relevant parametric information needed by the simulator, mainly through the use of the graphical user interfaces (GUIs). Modules are provided

for the specific models (e.g. radar, environment) which the simulator uses during execution. Tools are also provided to assist the user in understanding the effects of entered parameters for particular models. For example, a display tool showing the missile trajectory that results from the output of the missile dynamics model aids in designing useful scenarios. The simulator is also able to process target trajectory files with the required data structure. The simulator can run without the tracker, which allows us to focus on the detection beam processing. For more information on the features of ADAPT_MFR, how to use the simulation tool, and a detailed description of the implementation, see [2].

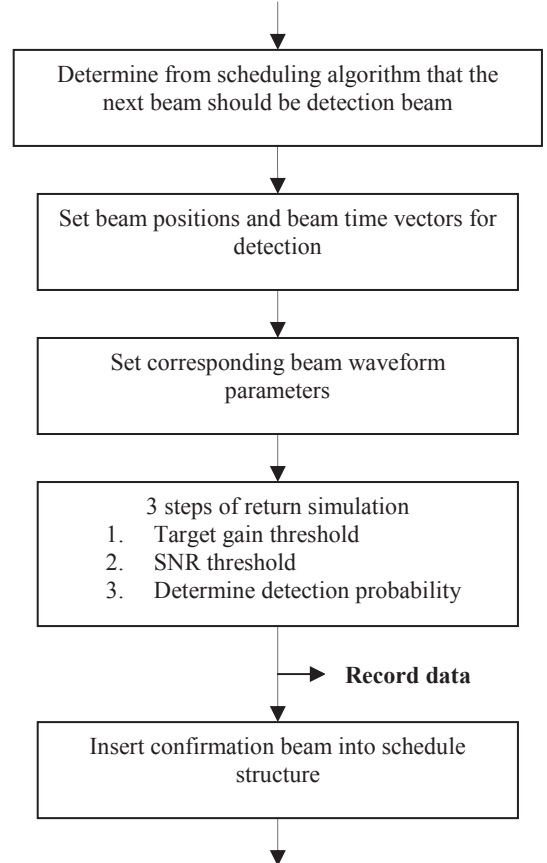


Figure 2: Event sequence for detection beams with a detection declared.

III. DETECTION PROCEDURE

Details of the event sequences with respect to the detection beams in the Adapt_MFR are presented in Figure 2, which shows the sequence of events that must occur for the simulation of a declared detection [4]. The implementation of this sequence of events in the Adapt_MFR is exploited for the simulation of on-the-fly scheduling of the Adapt_MFR. This is because the code that implements this scenario performs the steps necessary to schedule new tracks on-the-fly, as the existence of outdated tracking beams indeed necessitates the scheduling of new tracks. Detection data from the detection

beams are recorded for evaluation in Section 4.3. The data was collected whenever detection is declared.

IV. SIMULATION STUDY OF DETECTION COMBINATION ALGORITHMS

4.1 Radar setup for the study

The simulator is set up for a naval phased array multi-function radar at X-band. The radar's functions include horizon/surface search, detection confirmation, multi-target tracking and cued search.

The simulated radar has an aperture of 1 m^2 . The antennas are arranged in a square fashion and are mounted about 25 meters above the sea surface. Only one radar face is simulated. The complete frame time for the search function is 13.1 seconds for all search beams.

The radar waveform has an average PRF of 4.5 kHz, with a duty cycle of 23% and an extended pulse width of $50 \mu\text{s}$. The compressed LFM waveform provides 4 MHz of bandwidth, which indicates a compression factor of 200, and a resolution of 37.5 m. The transmit frequency varies between 9 and 11 GHz and can often span this whole range in a single dwell. The tracking waveform has a 30% duty cycle and 4 MHz of bandwidth. The waveform is organised into bursts with a switching PRF. The length of a burst is about 7 ms, which roughly results in 32 pulses per burst. Since the burst time is constant, however, the number of pulses will vary with the PRF. With 31 beams (2°) covering 60° , there is no additional beam overlap between adjacent dwells. Using 2 bursts per dwell, with PRFs of (4400, 4600) Hz, yields pulse numbers of (32, 32) per burst and an unambiguous Doppler frequency (for at least one of the two bursts) that easily accommodates a Mach 3 target.

The update rate for tracking is typically set as 1-4 Hz. The track waveform consists of two bursts, with a wide RF spacing and a selected burst time of 2 ms (the range is 1-7 ms). The track waveform has a duty cycle of 30%. The tracking beam is specified in ADAPT_MFR as a percentage, A 2 ms dwell time, occurring every 0.25 second, amounts to 8% time used for tracking. The processing features coherently integrated pulses (i.e. FFT/Doppler processing) and M/N binary detection. A probability of false alarm (Pfa) of 10^{-6} with 2/4 binary detection is used, which is consistent with the waveform design. Monopulse is available in both azimuth and elevation, and each receiver has about 69 dB of dynamic range and a noise figure of 7.5 dB. The signals are digitised at 5 MHz.

4.2 detection combination algorithms

When an association between detection and existing tracks fails, a confirmation beam would be issued and a tentative track would be initialized up on a successful confirmation.

Therefore, the multiple detections of the same target increase both the processing load and the false track rate.

The solution to remove the multiple detections is to combine those detections before any follow-up processing. There are two algorithms, which are given as follows. Each algorithm has three options: peak detection, average detection and weighted average detection. Average detection approach is used in this study.

- Cross-line combination (algorithm 1): all detections of the same target within the same frame are combined.
- In-line combination (algorithm 2): only detections within the same azimuth line are combined;

The purpose of this paper is to compare the above-mentioned algorithms and recommend one algorithm for implementation into the radar simulator.

4.3 Comparison of the two Detection combination algorithms

A single target scenario is used for the comparison:

- Initial range: 200 km;
- Initial speed: 248 m/s;
- Initial position in beam space is at $(-10^\circ, 3.75^\circ)$;
- Height: 1300 meters;
- RCS: 100 square meters;
- The target starts at 300 seconds and last 700 seconds.

Figure 3 shows the true trajectory of the simulated target in the beam space, where 2 degrees and 1.5 degrees of beam spacing are used for the azimuth and elevation, respectively. Surveillance field of view (FOV) is chosen to be 60 by 20 degrees. There are 434 beam positions in total and this makes the frame time of surveillance 13.1 seconds (using the radar setup in Section 4.1). Accordingly, each azimuth/horizontal line time is about 1 second. The tracking update is faster than the search.

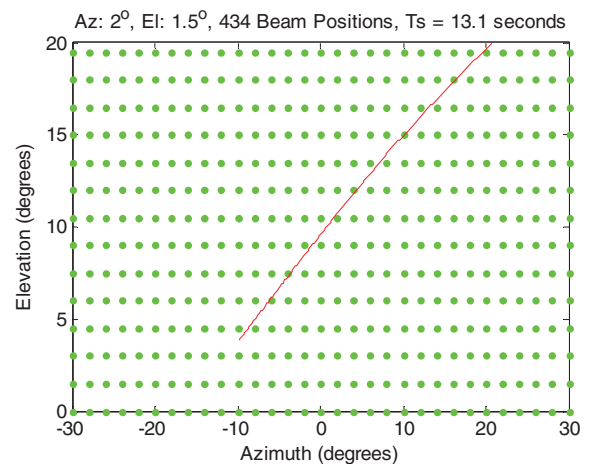


Figure 3: Surveillance beam and target position.

During the simulation period, 148 beams have detected the target (shown in Figure 4). The raw detection data were recorded from the Adapt_MFR simulator. The ground truth of the target and the accuracy were also recorded. The detection combination algorithms were tested outside of the radar simulator. 100 Monte Carlo simulations are used to compare the accuracy of the two algorithms.

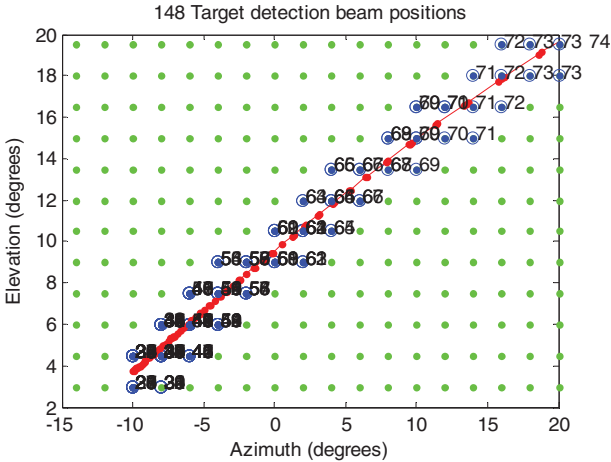


Figure 4: Target detection beam positions.

Figure 5 shows that the target was detected 14 times from the same beam position since a target at the far range is detectable for a longer time by the same beam position. An example is shown in Figure 6.

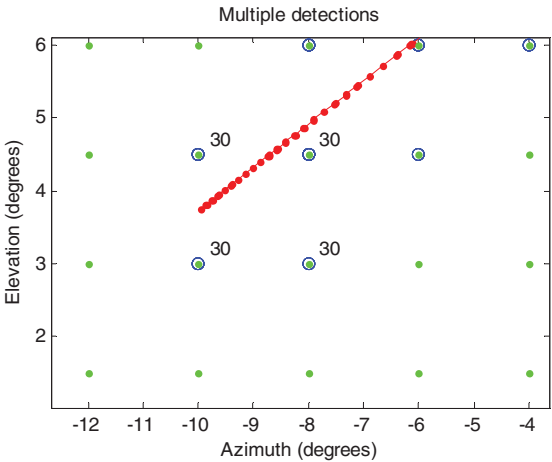


Figure 5: The test target was detected by 4 beams.

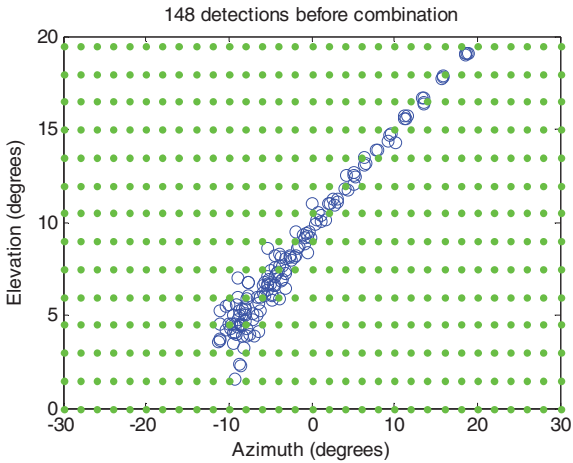


Figure 6: Radar detections before combination.

Figures 7 and 8 show the detections of the 100 Monte Carlo simulations after the combination. The original 148 detections were reduced to 52 (algorithm 1) and 107 (algorithm 2). The reduction of the detections greatly reduced the number of confirmation beams. This leaves more radar resources for other tasks.

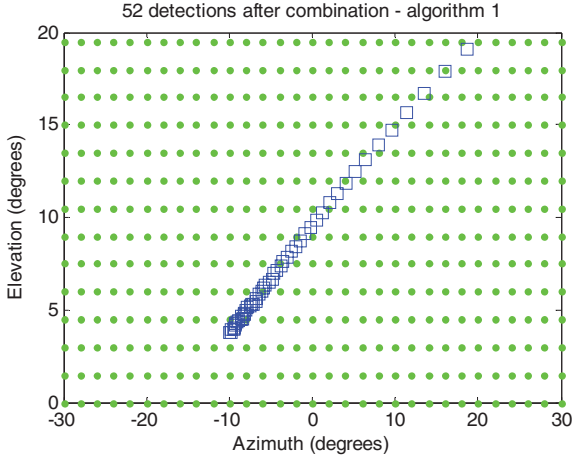


Figure 7: Cross-line detection combination (algorithm 1).

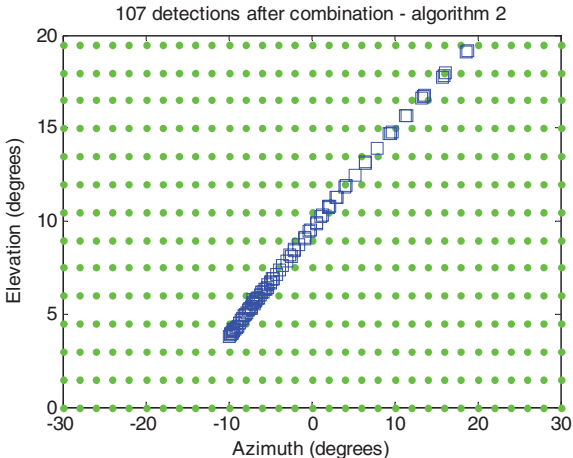


Figure 8: In-line detection combination (algorithm 2).

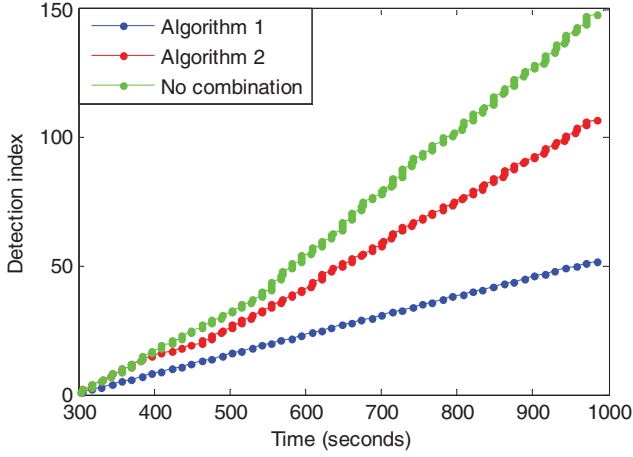


Figure 9: Comparison of detection numbers.

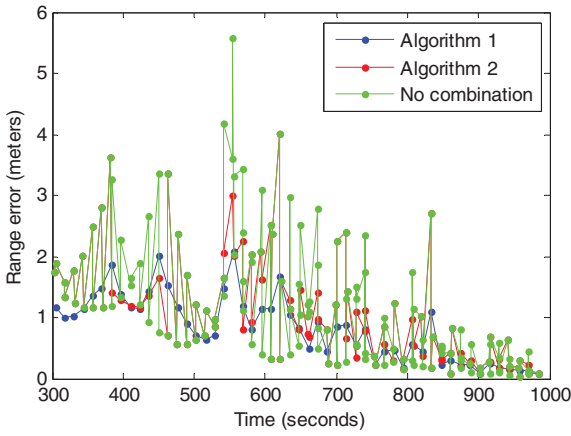


Figure 10: Range error comparison.

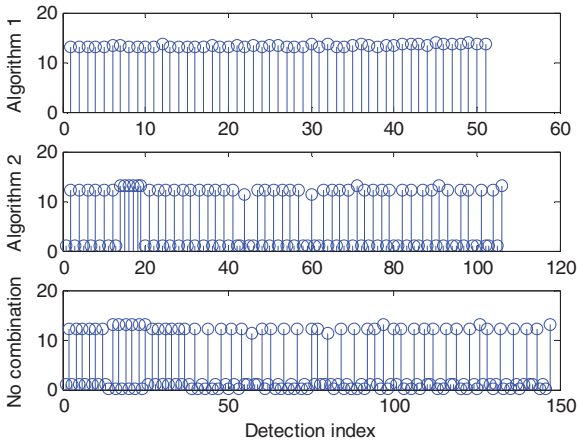


Figure 11: Comparison of detection interval.

Figures 9-11 compare the two algorithms in three aspects: (1) Increasing number of detections; (2) Radar range errors; (3) Detection interval of the same target.

It can be observed that algorithm 1 provides the most effective detection combination, the best accuracy and the most uniform detection interval. Algorithm 2 is the second in those three

areas; however, it needs less buffering and the detection delay is much less.

4.4 Further discussion

We have used a single search function and a single target for this study. It could be extended to multi-functions and multi-targets, where the following issues should be considered:

- All radar functions (search, confirmation, tracking and cueing) are considered together;
- Weighted average algorithm and peak gain algorithm are two other options. It is unknown how these algorithms perform;
- Multiple waveforms for many surveillance sectors are used. In particular, volume search and horizon search should be separately designed;
- Beam spacing has been a key factor. The narrower the beam space, the more detection generated by the radar and the longer the frame time is. The beam space should be optimized for the required performance. Figure 12 shows an example of 1° beam spacing in both azimuth and elevation dimensions. More detections are observed;
- In a multiple target situation, the detections should be discriminated into individual target before detection combination. When uncertainty exists, a feature-aided classifier is needed;
- This study assumes a horizontal line by line search scheme. Detection combination algorithms for a different search scheme (such as random) may perform differently and should be investigated accordingly.

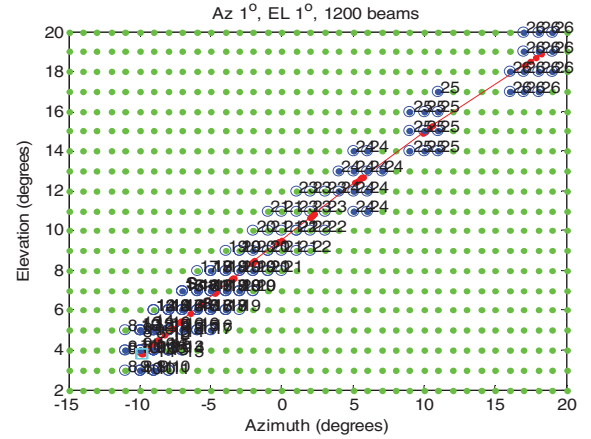


Figure 12: Radar detection from a beam space of 1 degree. The azimuth was limited to $[-15^\circ 20^\circ]$ for a better view.

V. CONCLUSION

This paper provides a comparison of two detection combination algorithms for multifunction phased array radars: cross-line combination and in-line combination. It is found that the cross-line combination algorithm needs buffer 2-3

lines of data and its delay is about 2-3 second. The in-line combination algorithm reduces the buffer data to only one line and its delay is about only 1 second. However, the first algorithm is able to remove about 2/3 of raw detections and the later can only reduce about 1/3 of the raw detection.

REFERENCES

- [1] D.R. Billetter, Multifunction array radar, Artech House, 1989.
- [2] G. Jones and T.J. Nohara, Final report for multi-function radar (MFR) simulator, Sicom Systems Ltd., Contract number W7714-020624/001/ZF, 2003.
- [3] E. McAfee, A new tracking algorithm for Adapt_MFR: combining IMM and NNJPDA, DRDC Ottawa TM 2005-241, 2005.
- [4] D. DiFilippo, E. McAfee, R. Chen, A. Moore and B. Dawber, A multifunction radar simulation for adaptive radar control studies, TR-SEN-1-2006.